# On Measuring Antiproton-Production Cross Sections at NICA SPD for Dark Matter Search

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05.10.2020

# Outlines

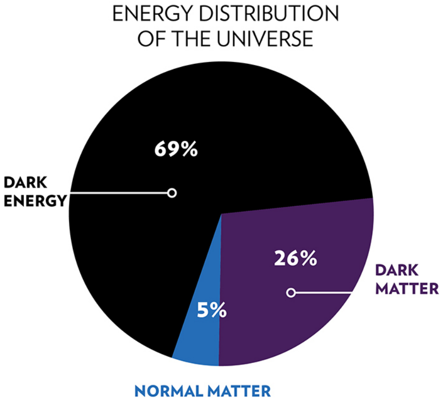


- Dark Matter
- Dark Matter Searches
- Uncertainties
- Available Data & Planned Measurements
- NICA SPD
- Preliminary MC Results
- SPD Coverage
- Requirements
- Conclusions

# Dark Matter



**Dark Matter ≡ Non-Luminous Matter**



# Evidence for Dark Matter

## Spiral Galaxies

# Evidence of Dark Matter
## Rotation Curves



| Predicted | Observed |
|---|---|

# Evidence of Dark Matter

## Rotation Curves



**Predicted Keplerian decline**

$$v(r) \propto \begin{cases} r, & r < R \\ \dfrac{1}{\sqrt{r}}, & r > R \end{cases}$$

**Observed plateau**

$$v(r) \begin{cases} \propto r, & r < R \\ \sim \text{constant}, & \\ \qquad \Downarrow & r > R \\ M(r) \propto r & \end{cases}$$

# Evidence of Dark Matter

## Galaxy Clusters



$$M_G \gg M_L$$

**Such discrepancy demonstrates the presence of dark matter in the galaxy cluster**

$$\text{Mass distribution} \begin{cases} 1\% & \text{Galaxies} \\ 9\% & \text{X-ray-emitting gas} \\ 90\% & \text{Dark matter} \end{cases}$$

# Evidence of Dark Matter
## Dark Lenses



Observing lensing effects without any apparent gravitational lenses indicates the presence of **dark lenses**.

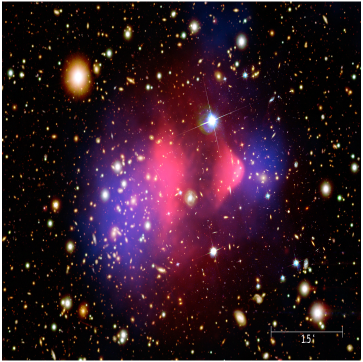
# Bullet Cluster

## The Smoking Gun



### Galaxies (Visible Light)

The galactic stars were not greatly affected by the collision, and most passed right through, gravitationally slowed but not otherwise altered.

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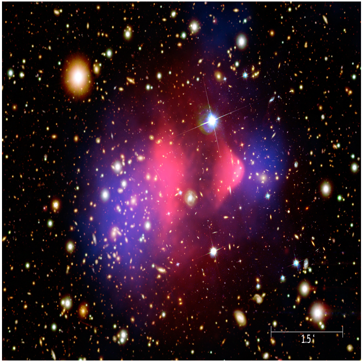
# Bullet Cluster

## The Smoking Gun



### Gas (Pink)

The hot X-ray-emitting gas represents most of the baryonic matter in the cluster pair; and interacts electromagnetically, thus slowing much more than the stars.

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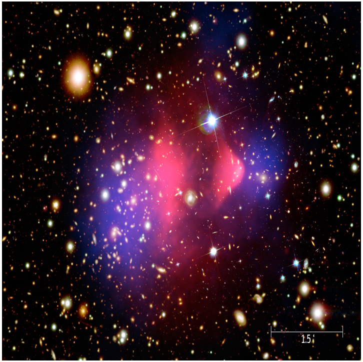
# Bullet Cluster
## The Smoking Gun



**Dark Matter (Blue)**

Lensing analyses of background objects show that the dark matter components bypassed the gas regions during the collision, showing that dark matter is only weakly interacting.

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# Dark Matter
## Candidates



### Candidates Classifications

- Production mechanism
  - Thermal
  - Non-thermal
- Particle nature
  - Baryonic
  - Non-baryonic
- Particle mass
  - Low mass (HDM)
  - Heavy (CDM)

# Dark Matter

## Candidates



### Most-Likely Candidates

1. **WIMPs** (Weakly Interacting Massive Particles)

# Dark Matter
## Candidates



### Most-Likely Candidates

1. **WIMPs** (Weakly Interacting Massive Particles)
2. MACHOs
3. Sterile neutrinos
4. SUSY particles
5. Axions
6. Kaluza-Klein candidates

# WIMPs
## Expected Properties



- Expected mass range $\sim 10$ GeV$-10$ TeV

# WIMPs
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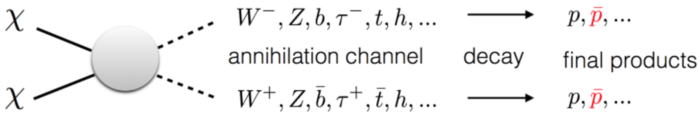
- Expected mass range $\sim$ 10 GeV$-$10 TeV
- Can elastically scatter on ordinary-matter nuclei
- Expected recoil energy $\sim$ 1 to 100 keV

# WIMPs

## Expected Properties

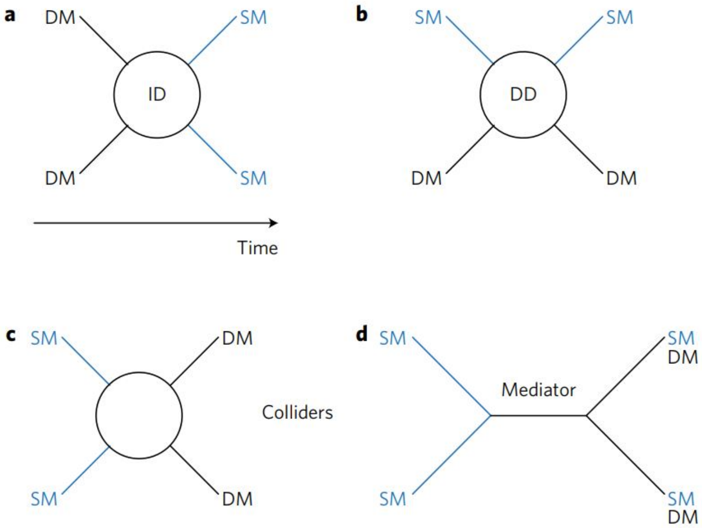


- Expected mass range $\sim$ 10 GeV$-$10 TeV
- Can elastically scatter on ordinary-matter nuclei
- Expected recoil energy $\sim$ 1 to 100 keV
- Can pair-annihilate and produce, through primary and secondary processes: $\nu, \gamma, e^+, \bar{p}$, and other anti-nuclei



# Search Approaches
## Underlying Hypotheses



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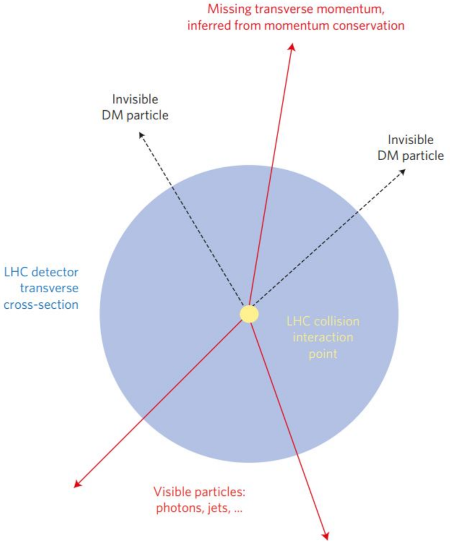
# Search Approaches

## Collider Searches

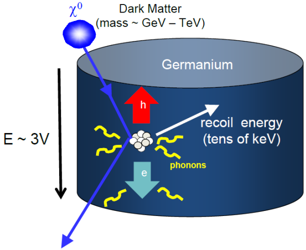


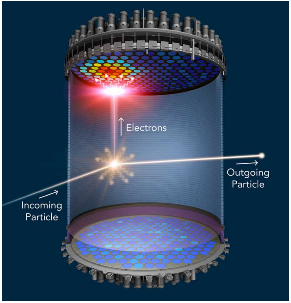



- ATLAS
- CMS

# Search Approaches
## Direct Detection






- Heat
- Ionization
- Scintillation

**Minimization** and **identification** of signal backgrounds are crucial.

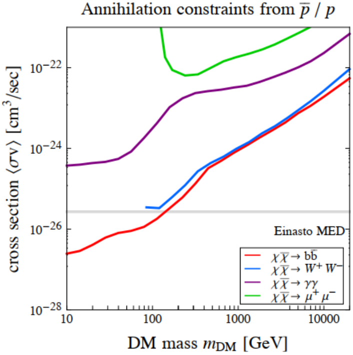
Retrieved from ©KIPAC.

# Search Approaches

## Indirect Detection



- Spectral distortion of CRs
- Pair-annihilation and decay of WIMPs
- Targeted products: $\nu$, $\gamma$, $\bar{p}$, $e^{+}$
- Experiments:
  - Ground-based ($\gamma$): H.E.S.S., MAGIC, VERITUS
  - Satellite-borne: FREMI-LAT ($\gamma$), PAMELA, AMS-02

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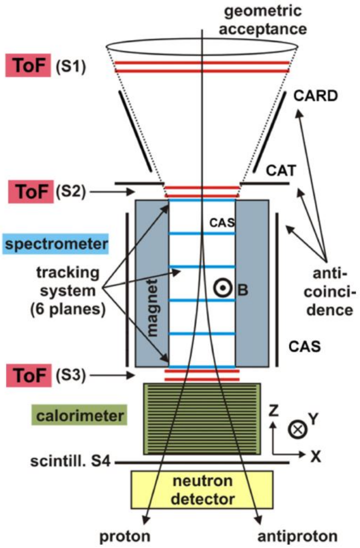
# Astrophysical Searches

## PAMELA Magnetic Spectrometer





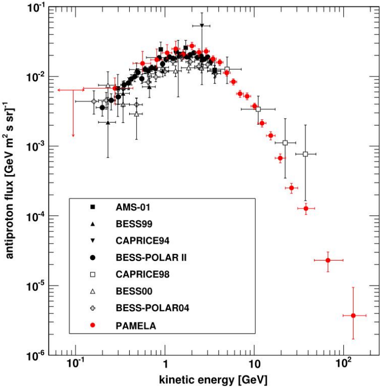

Measuring antiparticle fluxes in primary CRs from June 2006 to Feb. 2016

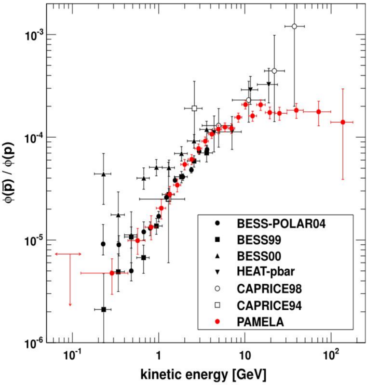
Physics Reports 544 (2014) 323–370

# Astrophysical Searches
## PAMELA Antiproton Results



PAMELA $\bar{p}$ results for 2006 – 2009
$T_{\bar{p}}$ = 80 MeV - 190 GeV



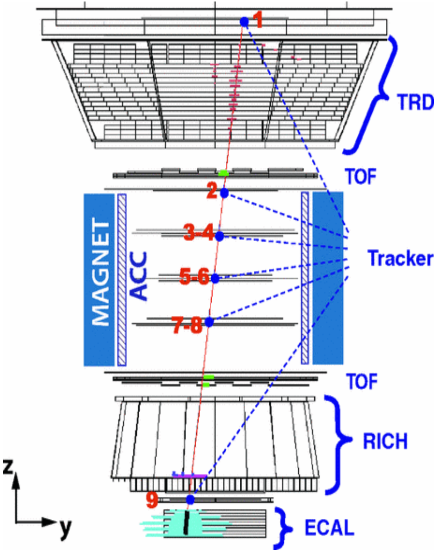




Physics Reports 544 (2014) 323–370

# Astrophysical Searches

## The Alpha Magnetic Spectrometer (AMS-02)






Measuring charged CR flux since May 2011

(AMS) PRL 110, 141102 (2013)

# Astrophysical Searches

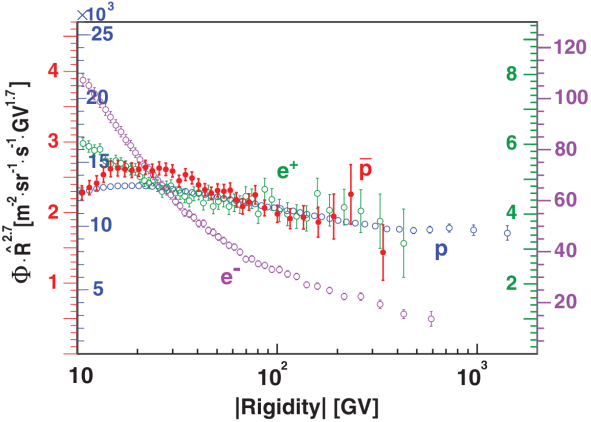
## AMS-02 Results



AMS-02 $\bar{p}$ results for 2011 – 2015

$p_{\bar{p}} = 1 - 450$ GeV

$R = pc/q$ [Volt]

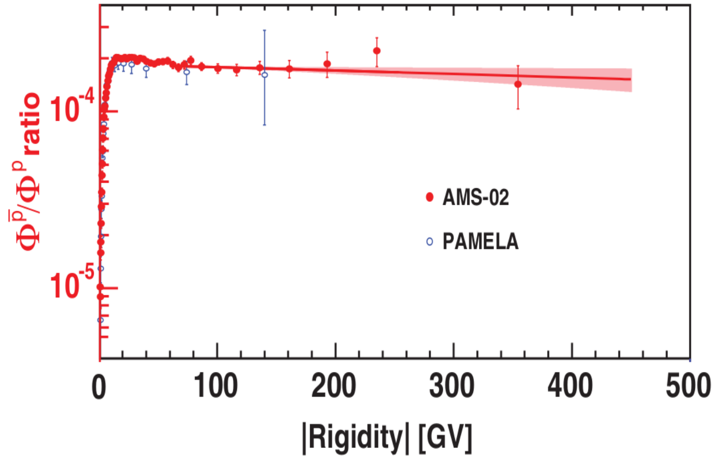



(AMS Colab.) PRL 117, 091103 (2016)

# Astrophysical Searches
## AMS-02 Antiproton Results



Error $< 5\%$




(AMS Colab.) PRL 117, 091103 (2016)

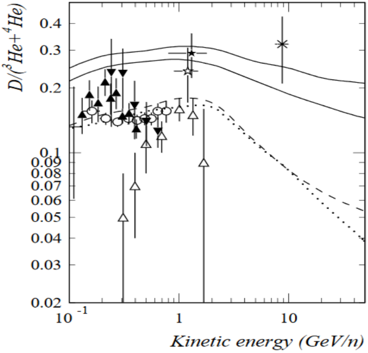
# Secondary CRs

## Light Nuclei Abundances



**Collisions of primary CRs and ISM**

| Nuclei | CRs | ISM |
|---|---|---|
| $p$ | 0.844 | 0.911 |
| $D$ | 0.029 | $1.6 \times 10^{-5}$ |
| $^{3}$He | 0.027 | $2 \times 10^{-5}$ |
| $^{4}$He | 0.10 | 0.089 |

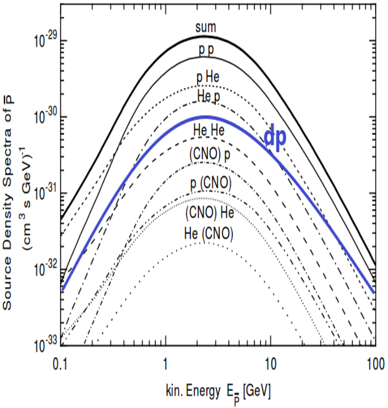


# Secondary CRs

## $\bar{p}$ Production Channels



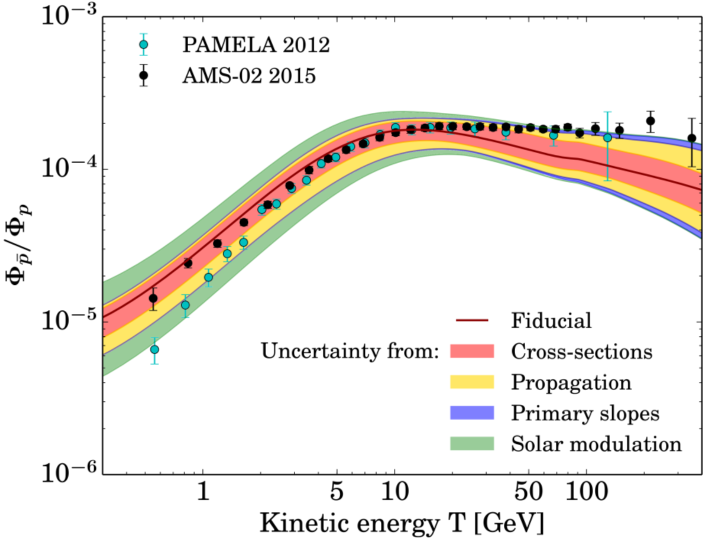
| Collision | $\bar{p}$ yield | Normalized |
|---|---|---|
| $pp$ | 64% | 1 |
| $p^4$He | 26% | 0.4 |
| $^4$He$^4$He | 0.9% | 0.014 |
| $pD$ | 3.9% | 0.06 |
| $p^3$He | 5.2% | 0.08 |



# Uncertainties

## Sources



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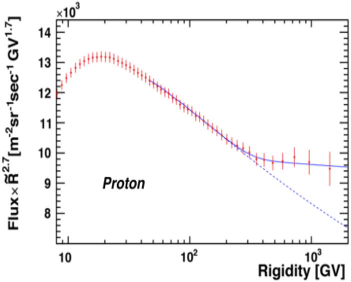
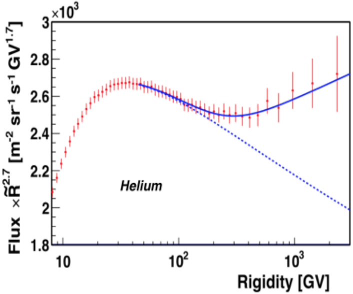
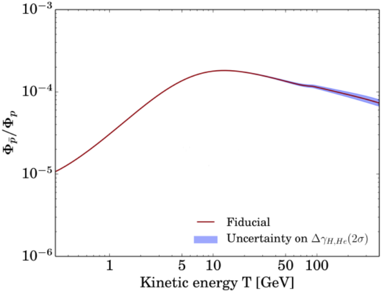
# Uncertainties
## Primary Spectra Slopes



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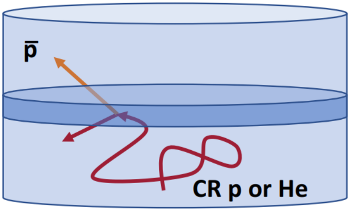
# Uncertainties

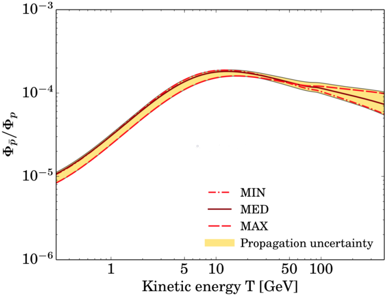
## Galactic Propagation Parameters



**Diffusion and convection parameters**




$$\mathrm{CR}_i + \mathrm{ISM}_j \to \bar{p} + X$$

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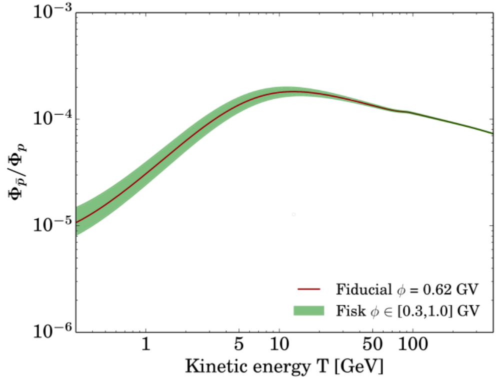
# Uncertainties
## Solar Modulation



Solar modulation depends on the solar activity at the time of observation.

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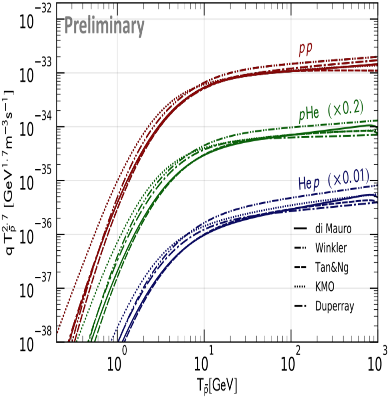
# Uncertainties

## Production Cross Sections

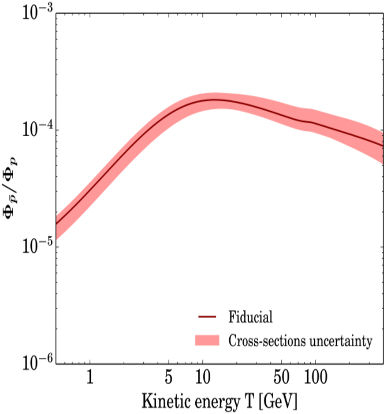


Channel parameterizations

$\sim 20 - 50\%$




Phys. Rev. D 96 (2017) 043007

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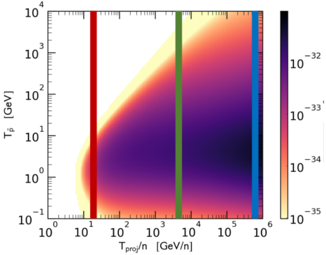
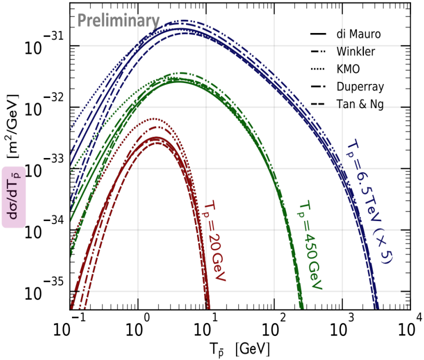
# Uncertainties

## Production Cross Sections



- Reasonable agreement for $T_{\bar{p}} > 10$ GeV and $T_p$ above a few 100 GeV
- Significant deviation for $T_{\bar{p}}$ below a few GeV




Phys. Rev. D 96 (2017) 043007

# Available $\sigma_{\bar{p}}$ Data

## $p - p$ Collisions



Radial-scaling variable: $x_R = \frac{E_{\bar{p}}}{E_{\bar{p}.max}}, \quad E_{\bar{p}.max} = \frac{s - 8m_p^2}{2\sqrt{s}}$

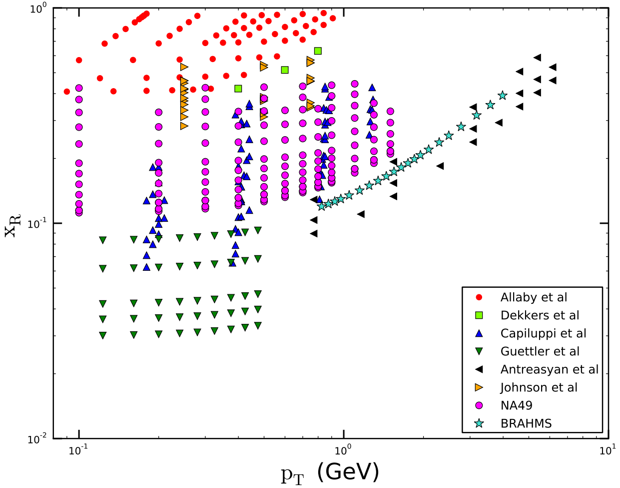
| Experiment | $\sqrt{s}$ (GeV) | $P_T$ (GeV) | $x_R$ |
|---|---|---|---|
| Dekkers *et al.*, CERN 1965 | $6.1, 6.7$ | $(0.00, 0.79)$ | $(0.34, 0.65)$ |
| Allaby *et al.*, CERN 1970 | $6.15$ | $(0.05, 0.90)$ | $(0.40, 0.94)$ |
| Capiluppi *et al.*, CERN 1974 | $23.3, 30.6, 44.6, 53.0, 62.7$ | $(0.18, 1.29)$ | $(0.06, 0.43)$ |
| Guettler *et al.*, CERN 1976 | $23.0, 31.0, 45.0, 53.0, 63.0$ | $(0.12, 0.47)$ | $(0.036, 0.092)$ |
| Johnson *et al.*, FNAL 1978 | $19.4, 23.8, 27.4$ | $(0.77, 6.15)$ | $(0.08, 0.58)$ |
| Antreasyan *et al.*, FNAL 1979 | $23.0, 31.0, 45.0, 53.0, 63.0$ | $(0.12, 0.47)$ | $(0.036, 0.092)$ |
| BRAHMS, BNL 2008 | $200$ | $(0.82, 3.97)$ | $(0.11, 0.39)$ |
| NA49, CERN 2010 | $17.3$ | $(0.10, 1.50)$ | $(0.11, 0.44)$ |
| NA61, CERN 2017 | $6.3, 7.7, 8.8, 12.3, 17.3$ | — | — |

PEPAN Lett. 16 (2019) 03

# Available $\sigma_{\bar{p}}$ Data

$p - p$ Collisions





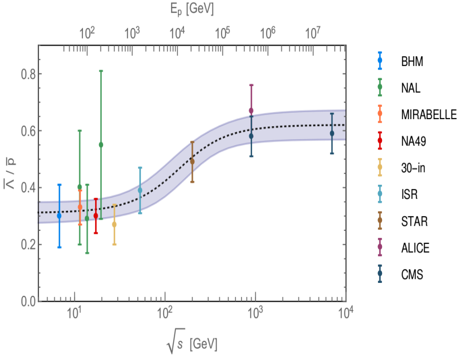

Phys. Rev. D 90 (2014) 085017 ©APS 2014

# Available $\sigma_{\bar{p}}$ Data

## Other Channels



- $1^{\text{st}}$ $(p + He \to \bar{p} + X)$ data set only in 2018 by LHCb
- No measurements for other channels

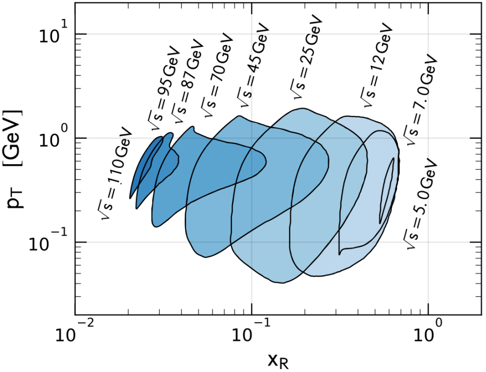



No hyperon feed-down in older datasets

JCAP 02 (2017) 048

## Coming to conclusions about a DM $\bar{p}$-signal in the AMS-02 measurements

- 3% inside
- 30% outside




Phys.Rev.D96(2017)043007©APS 2017

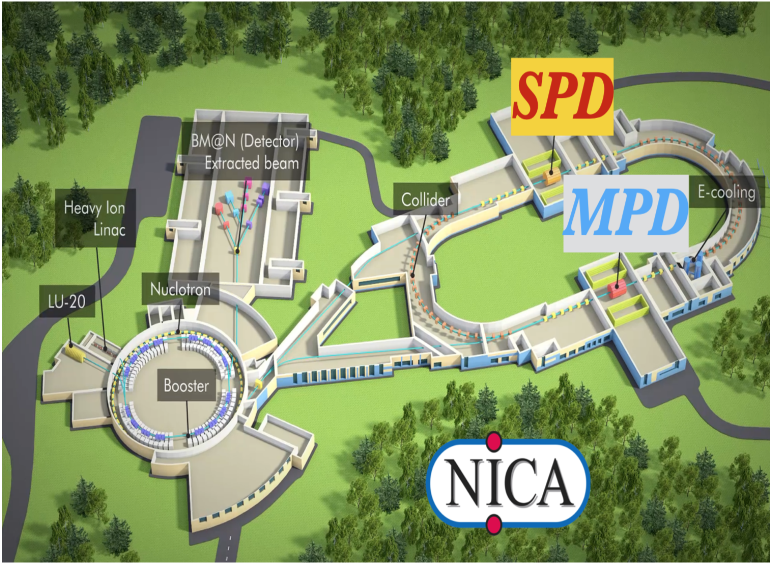
# Planned Measurements

## Outlook



- Continuing $pHe$ measurements at LHCb after the fixed-target $\sqrt{s} = 114$ GeV measurement.
- All LHCb measurements are expected to be in the high-energy range.
- COMPASS++/AMBER plans fixed-target $pp$ and $pHe$ measurements at CERN SPS for $\sqrt{s} \sim 9 - 20$ GeV.

# The Nuclotron-based Ion Collider fAility (NICA)



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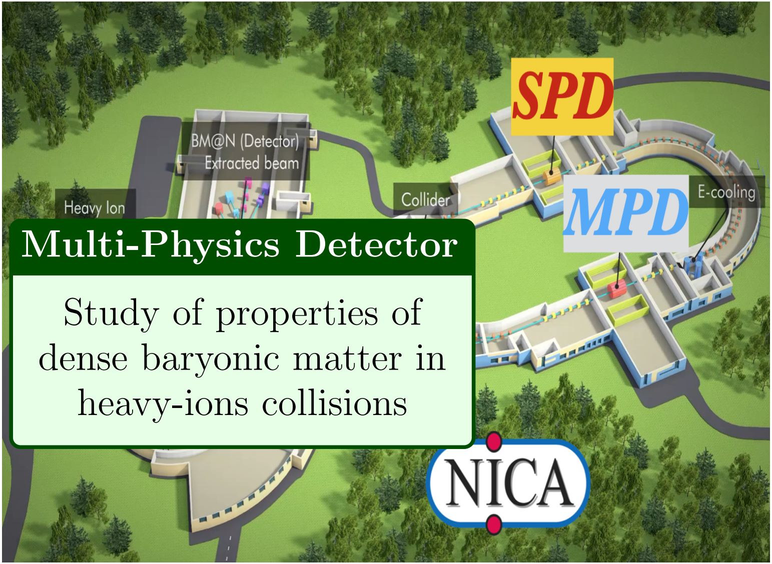
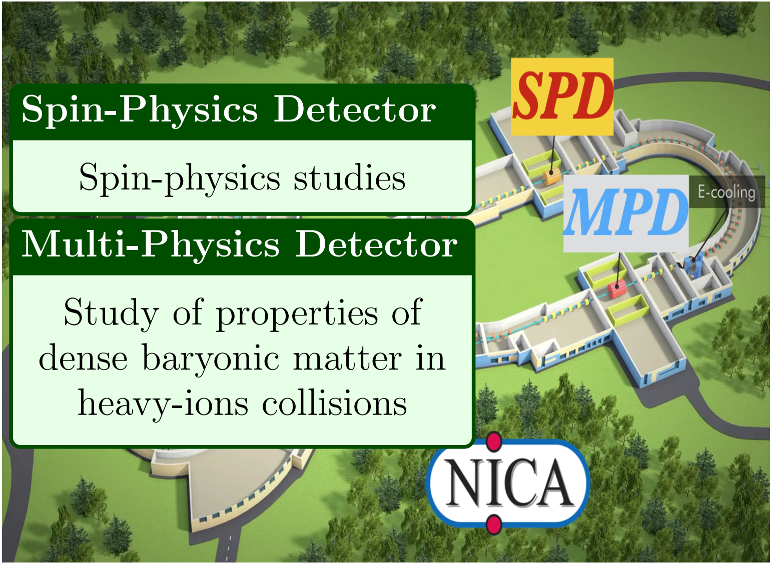



**Multi-Physics Detector**

Study of properties of dense baryonic matter in heavy-ions collisions

# The Nuclotron-based Ion Collider fAility (NICA)




**Spin-Physics Detector**

Spin-physics studies

**Multi-Physics Detector**

Study of properties of dense baryonic matter in heavy-ions collisions

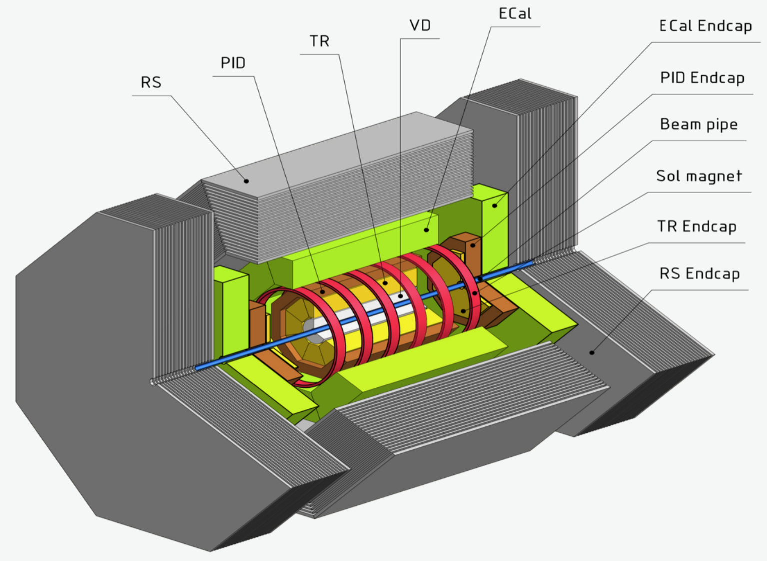
# The Nuclotron-based Ion Collider fAility
## NICA & SPD



- Planned to use polarized $p$, $D$, and possibly, $^3He$ ions in the 2nd stage.
- Possibility to collide any available polarized particles: $pp$, $pD$, and $p^3$He.
- Planned kinetic energies for $p \sim 5 - 12.6$ GeV; and for $D \sim 4 - 11.8$ GeV.
- At $\sqrt{s} = 27$ GeV in $pp$ collisions, $L = 10^{32}$ cm$^{-2}$ s$^{-1}$ should be achievable.

# Spin-Physics Detector (SPD)
## Setup

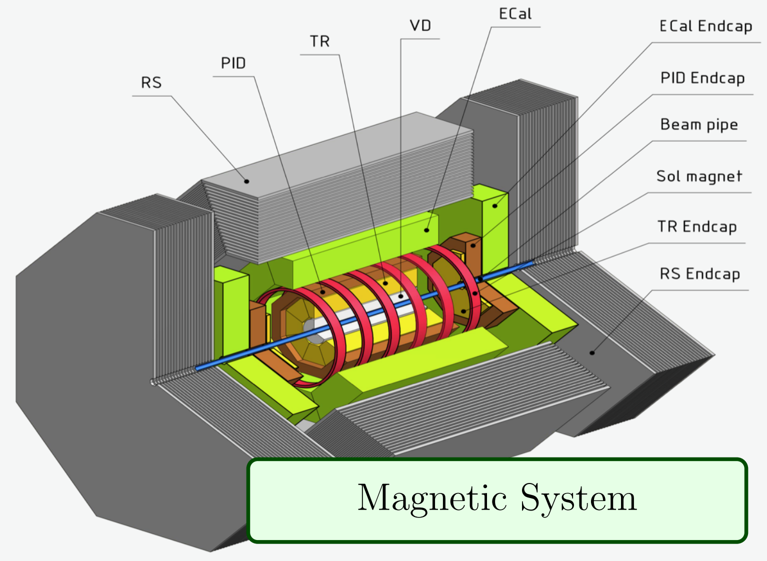




# Spin-Physics Detector (SPD)

## Setup



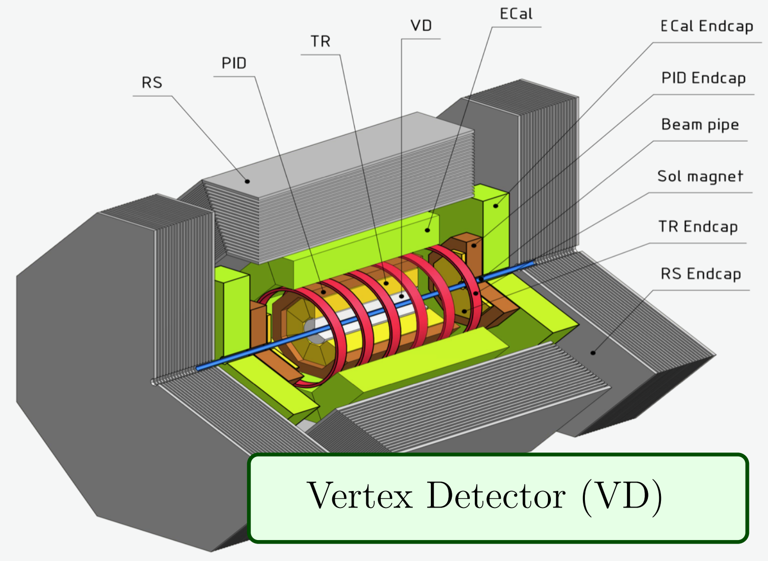



Magnetic System

# Spin-Physics Detector (SPD)

## Setup



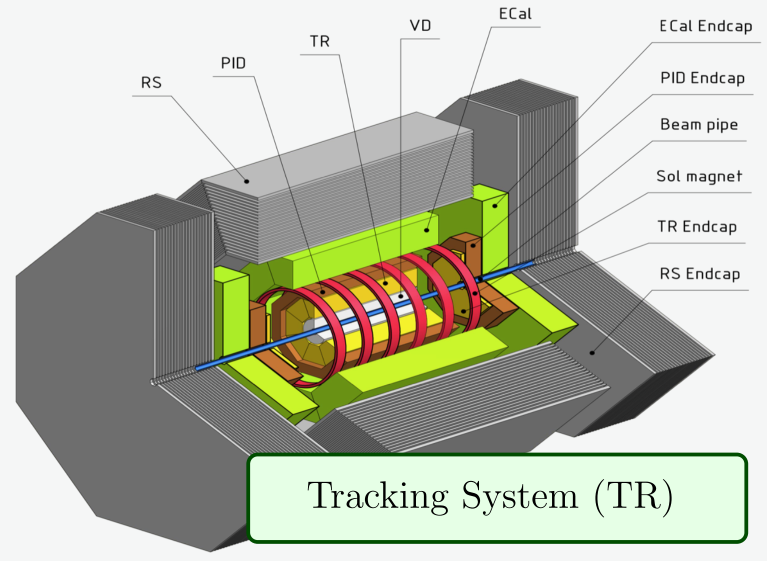



Vertex Detector (VD)

# Spin-Physics Detector (SPD)

## Setup



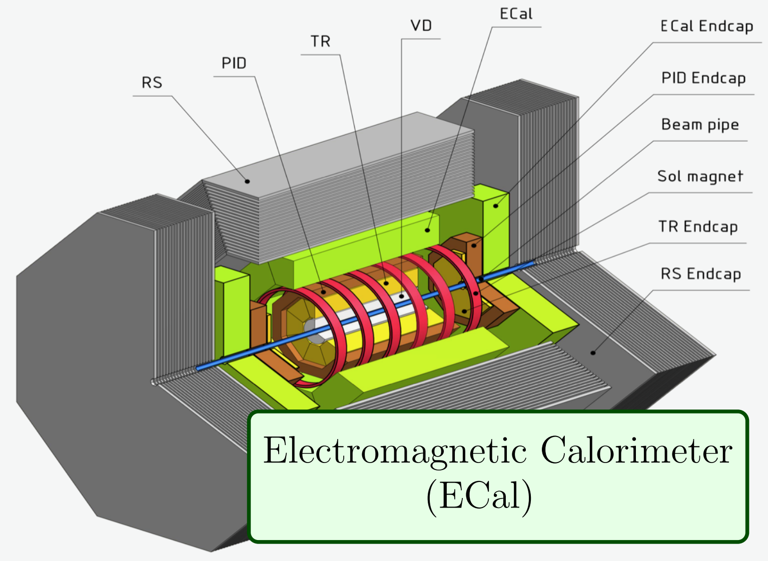



Tracking System (TR)

# Spin-Physics Detector (SPD)

## Setup



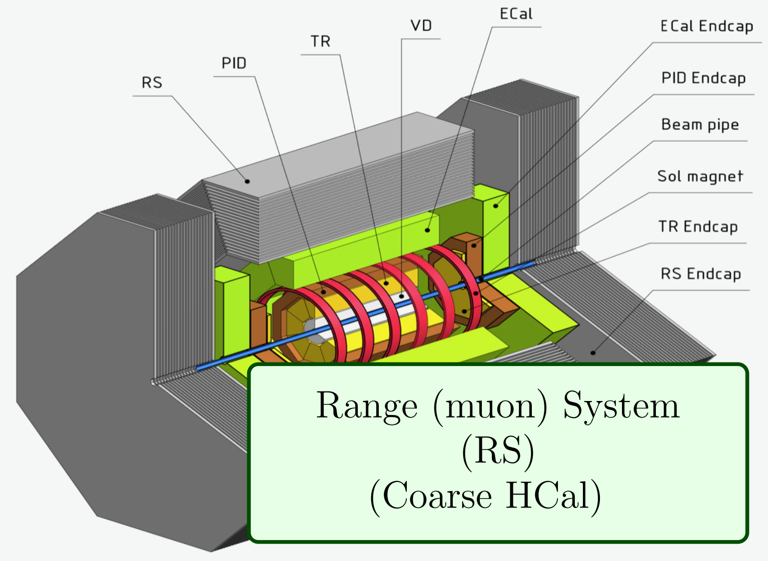



Electromagnetic Calorimeter (ECal)

# Spin-Physics Detector (SPD)

## Setup



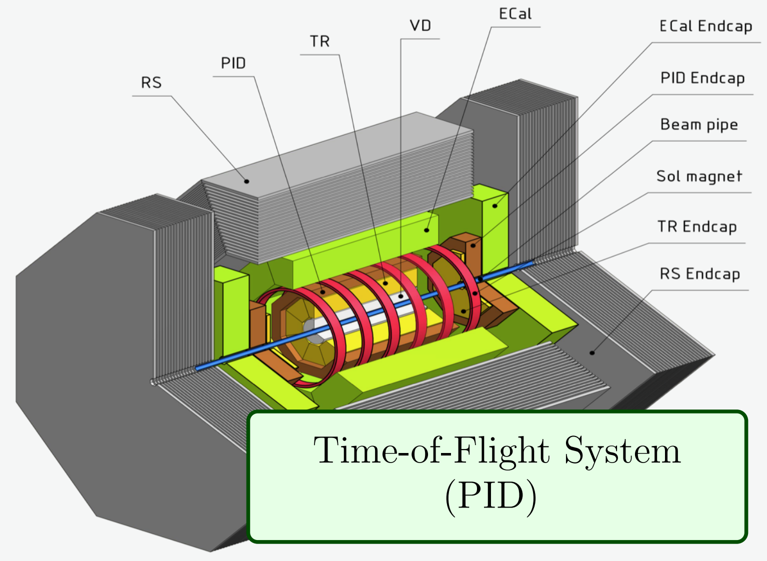



Range (muon) System (RS) (Coarse HCal)

# Spin-Physics Detector (SPD)

## Setup



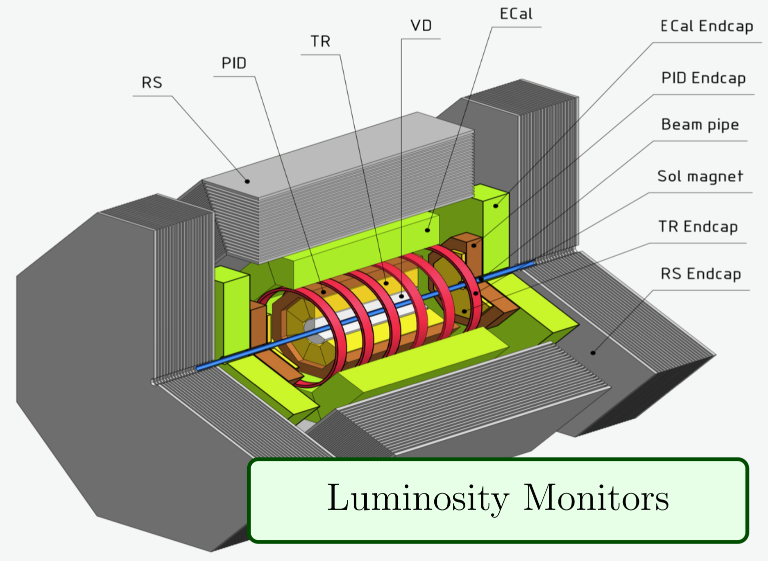



Time-of-Flight System (PID)

# Spin-Physics Detector (SPD)

## Setup



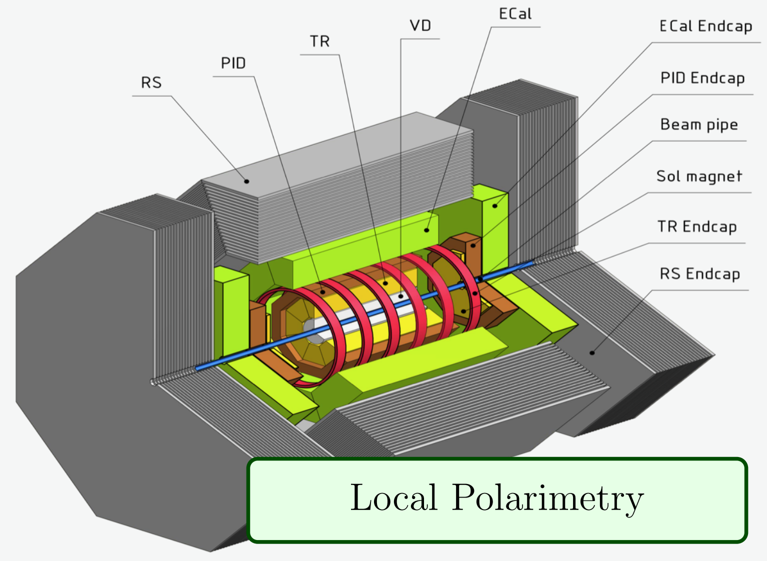



Luminosity Monitors

# Spin-Physics Detector (SPD)

## Setup





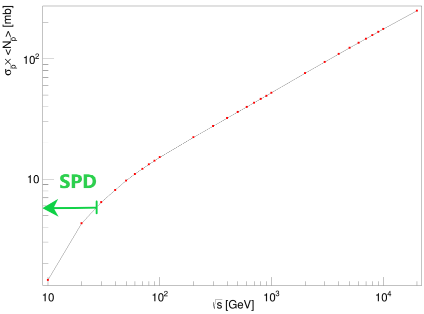

Local Polarimetry

# Preliminary MC Results
## $\bar{p}$ Production & Yields



PYTHIA8 wide-range results

$$\boxed{\sigma_{\bar{p}}(\sqrt{s} = 26 \text{ GeV}) \sim 33 \text{ mb}}$$




PEPAN Letters 16 (03) 2019

$$\sqrt{s} = 26 \text{ GeV}$$

| Channel | % |
|---|---|
| Direct | 37.3 |
| $\bar{n}$ decay | 36.9 |
| $\bar{\Lambda}$ decay | 19.8 |
| $\bar{\Sigma}^-$ decay | 6.0 |

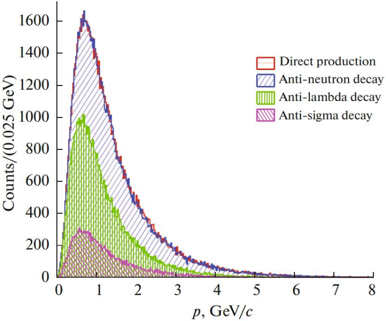
hyperons' $\bar{p}$
$\sim 25\%$

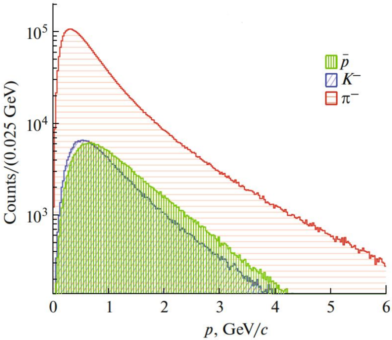
# Preliminary MC Results

## Momenta & PID



Most $\bar{p}$'s have $p < 5$ GeV



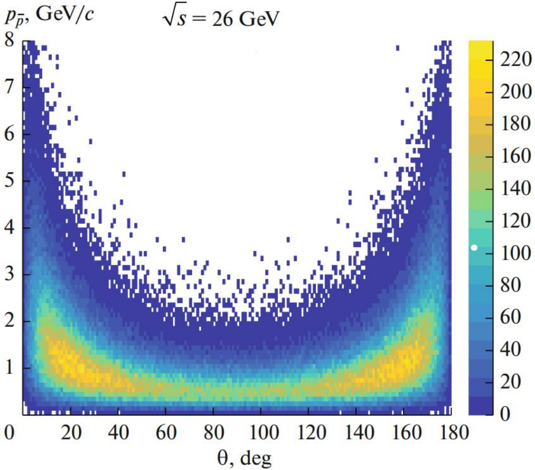

$K^-/\bar{p}$ separation up to $p \sim 5$ GeV for $\sigma_{ToF} < 60$ ps

PEPAN Letters 16 (03) 2019

# Preliminary MC Results
## Angular Distribution



SPD $4\pi$-angular acceptance is an advantage

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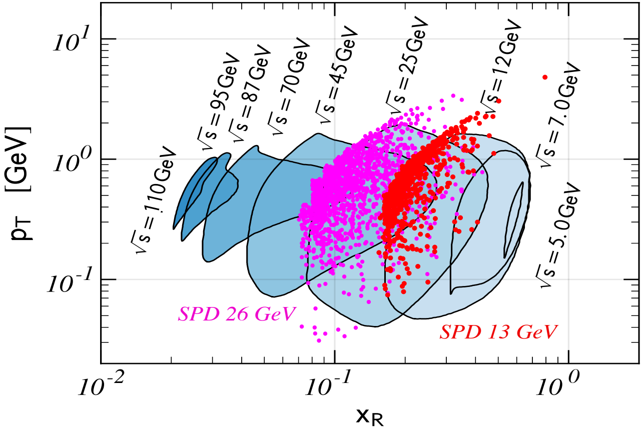
# SPD Coverage

## $\bar{p}$ Phase-Space Contribution



Accessible kinematic range of $\bar{p}$'s produced in $pp$ collisions.



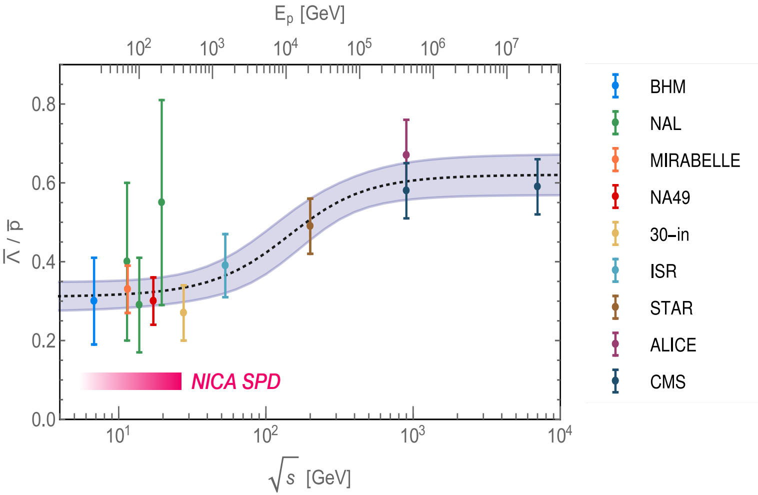

arXiv:2008.04136 **[hep-ex]** (2020)

# SPD Coverage

## $\bar{\Lambda}/\bar{p}$ Measurement



$\bar{\Lambda}/\bar{p}$ uncertainties in previous datasets for SPD energies $\sim 12\%$.



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- Time resolution $\lesssim 70$ ps (for accurate PID)
- Secondary-vertices reconstruction
(for hyperon-decay investigation)
- Precision luminosity monitor, $\lesssim 3\%$
(for accurate $\sigma_{\bar{p}}$ evaluation)

# Conclusions



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- The collider mode and $4\pi$-geometry of SPD provide a unique possibility to study $\bar{p}$-production at high $p_T$.
- The main requirements for performing the measurements would be an advanced PID (ToF system), precision reconstruction of secondary vertices, and precision luminosity monitoring.
- Possibility of measurement extension by potential inclusion of light-nuclei beams ($^3He$, $^4He$) at NICA.

# Conclusion



**The proposed supplementary measurements at the SPD could make a sizable contribution to the search of physics beyond the Standard Model.**

# Thank You!